2D Discrete Element Modeling and Experimental Results of Proppant Embedment into Fracture Walls

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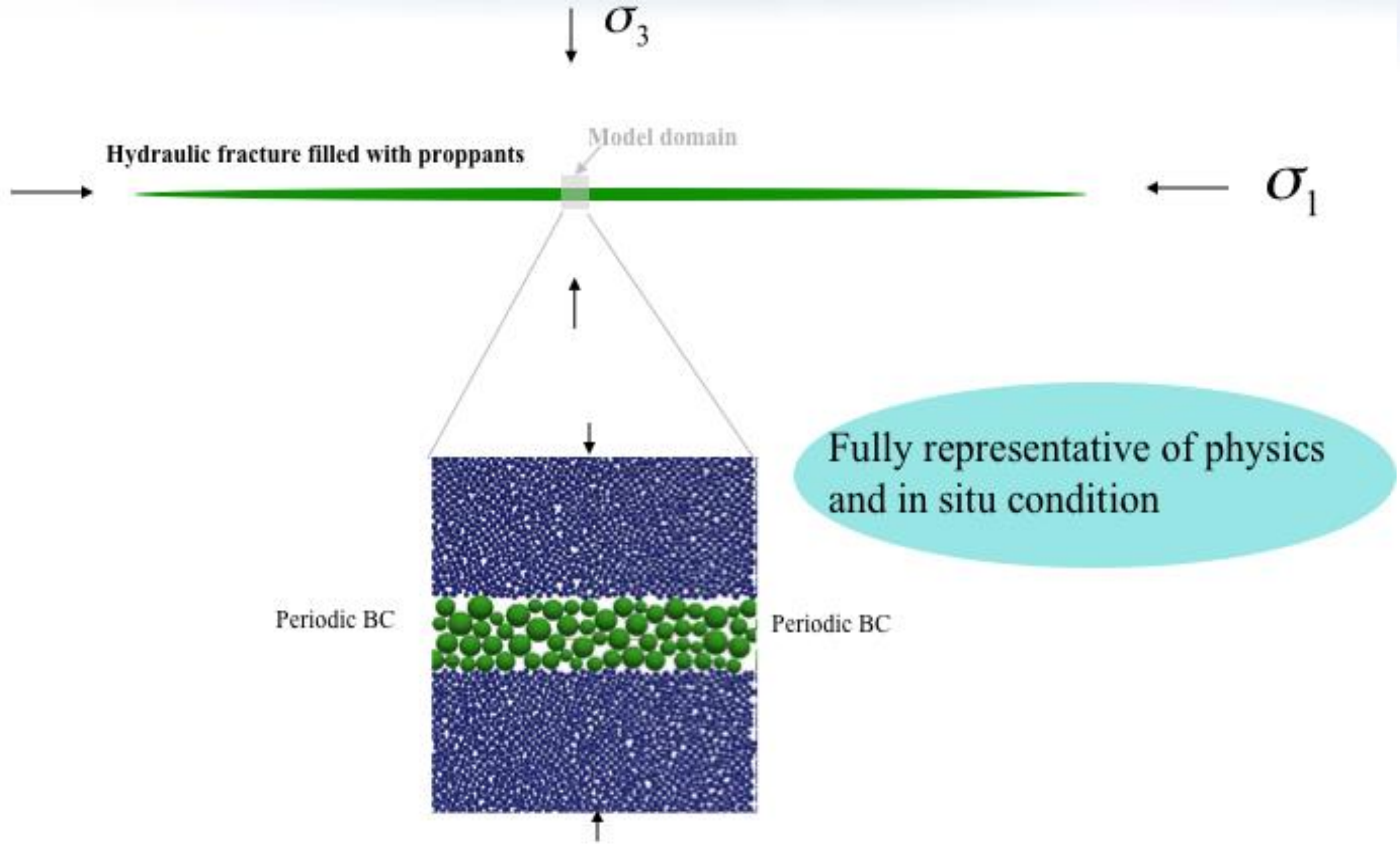
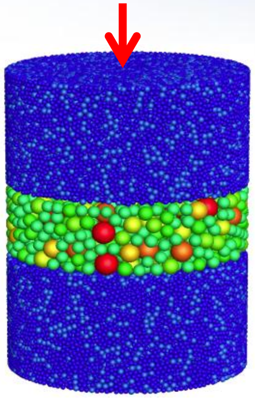
Proppant-Shale Mechanical Interactions

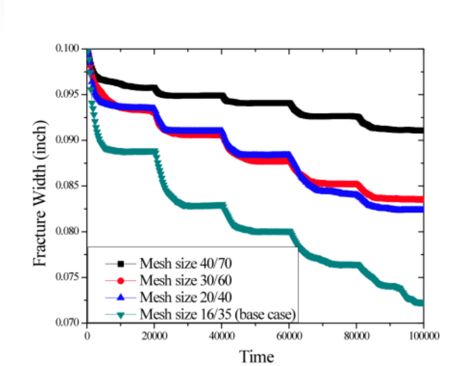


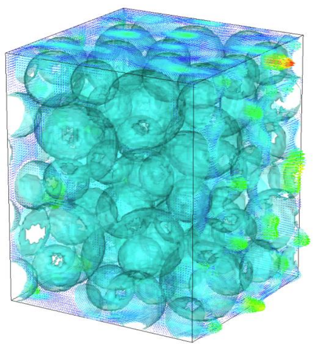
- Stress concentrations
- Aperture & permeability as function of:

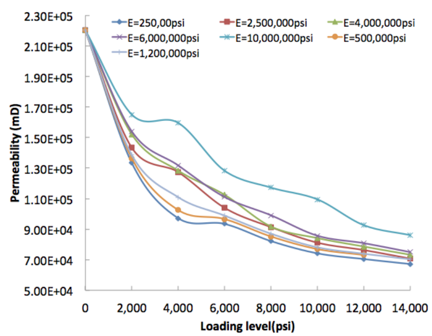
stress, shale modulus, proppant size, yield strength etc.

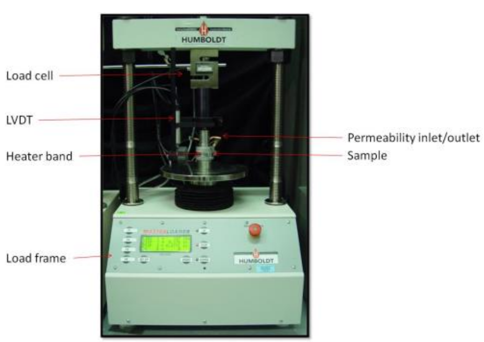
Research Approaches: Integrated Modeling & Experiment

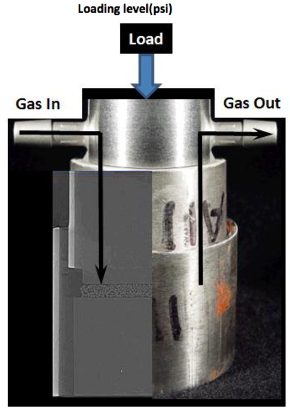












1. **Discrete element model (DEM) for modeling proppant embedment into shale under high stress:**
   - ✓ ***Deformation of fracture walls***
   - ✓ ***Reduction of aperture as function of proppant size and rock stiffness***
   - ✓ ***Porosity changes due to repacking***
2. **Pore-scale flow simulations**
   - ✓ ***Use pore geometries and fracture walls obtained by DEM as input***
   - ✓ ***Solving Navier-Stokes in pores***
   - ✓ ***Calculate permeability vs. stress***
3. **High-temperature, high-stress proppant embedment experiments**
   - ✓ ***Model validation and calibration***
   - ✓ ***X-ray tomography***

Testing Outline

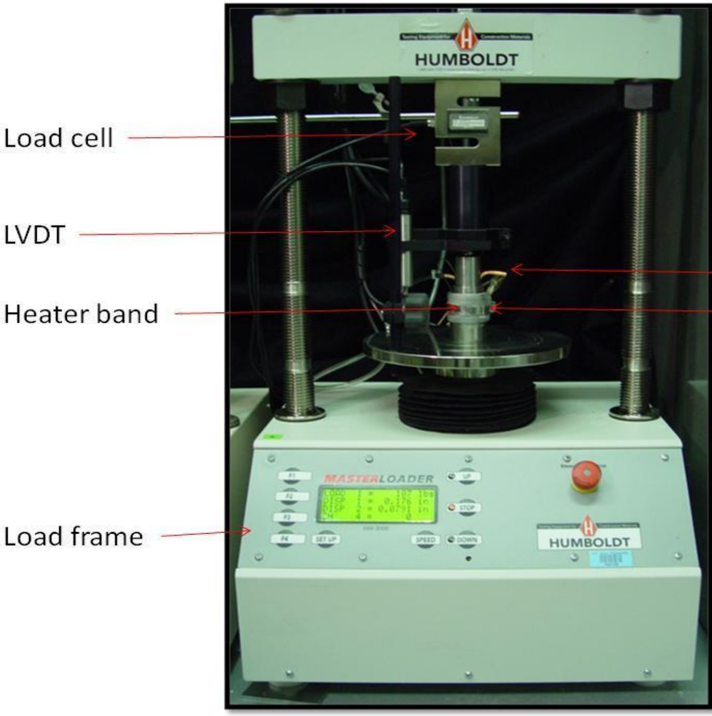
Carbo Ceramic API RP-61

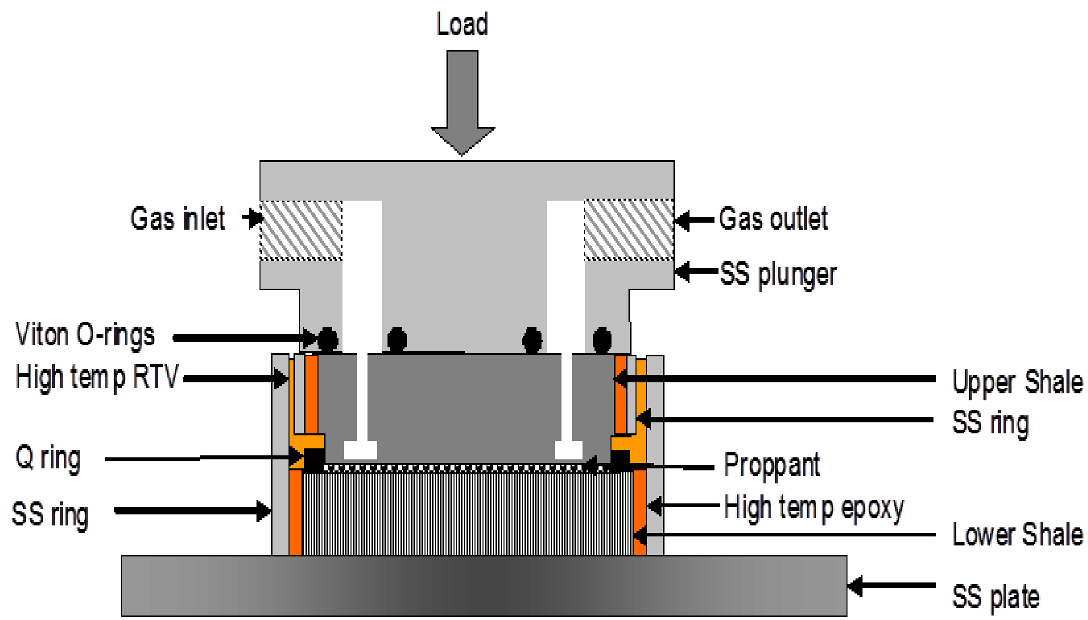
- Load to 2 lbs/sq ft
- Purge 2% KCl solution w/ oxygen-free nitrogen
- Apply a vacuum for 45 minutes
- Flow 2% KCl soln. through heated silica sand
- Ramp to 1000 psi and 500 psi fluid pressure
- Heat cells to 250ºF (or other temperature)
- Increase stress to 2,000 psi
- Flow fluid at rates of 3, 4 and 6 ml/min. Measure *P* 30 minutes after each step change in flow rate
- Measure propped fracture width and temp.
- Maintain stress for 50 hours
- Increase stress @ 2,000 psi increments for 50 hrs
- Continue measuring p at 3, 4 and 6 ml/min of fluid flow, frac width and temperature until 14,000 psi stress is reached.

INL Validation Tests

- Load to 1 lb/sq ft
- Purge w/ nitrogen
- Ramp to 200 psi @ 0.009 in/min
- Heat cells to 175ºC @ 1 C per min
- Flow fluid at 300 cc/min and measure *P* @ 1 minute intervals
- Increase stress to desired psi @ 0.009 in/min
- Flow fluid at 300 cc/min and measure *P* @ 30 minutes intervals
- Also recording sample height and temp.
- Maintain stress for ~50 hours (~2 days)
- Current system can achieve 10,000 psi stress

INL's Experimental Set-up

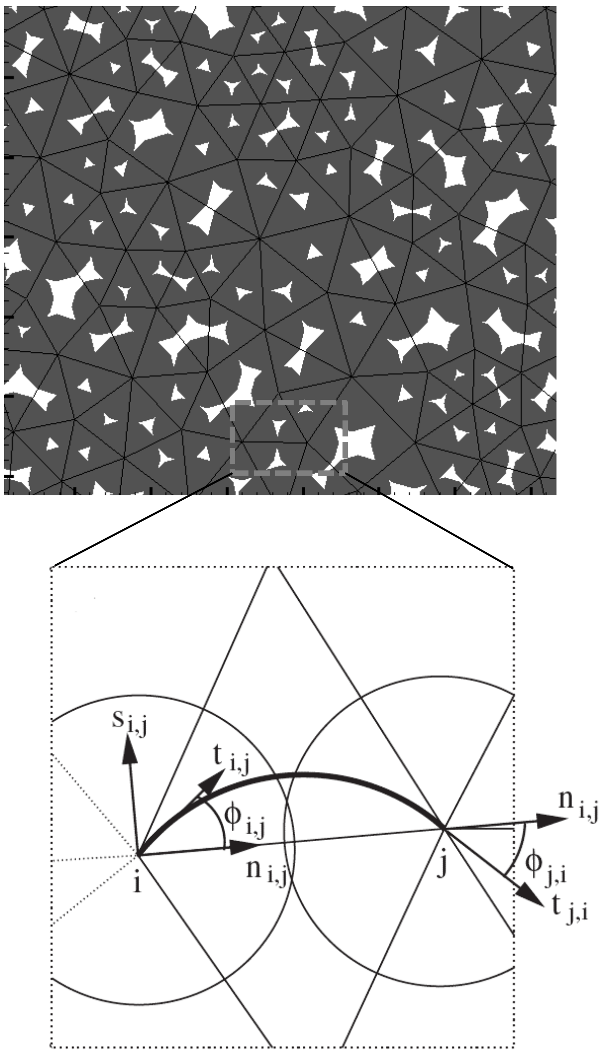




- ➢*Loading stress up to 10,000psi*
- ➢*Temperature up to 200°C*
- ➢*Lateral confining stress*

Discrete Element Method (DEM) For Meso-scale Fracturing Simulations

DEM Model Framework



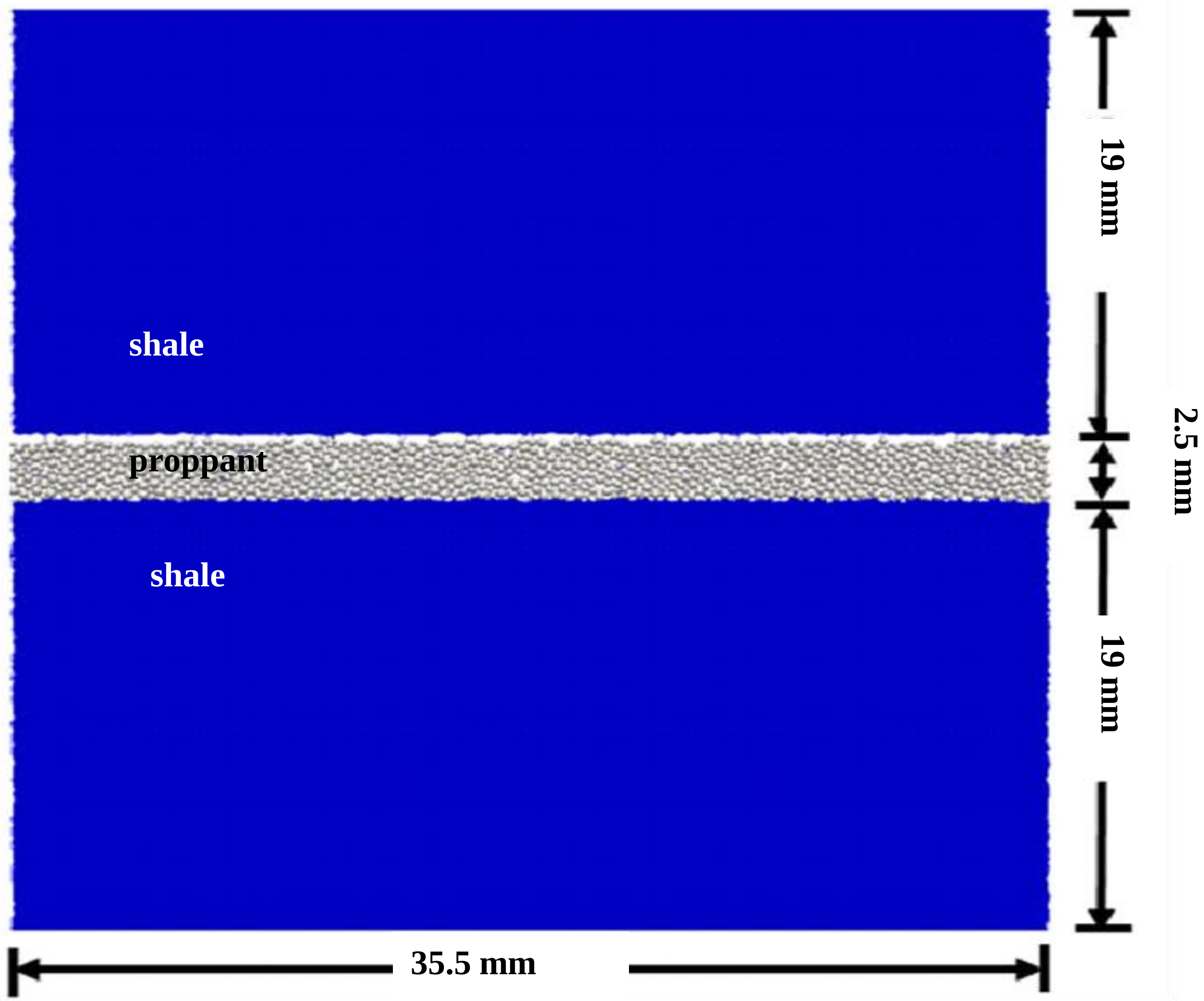
- Represent material, including heterogeneity and anisotropy, by a network of mechanical elements (springs, beams, viscoelastic, etc.)
- Impose boundary conditions (stress, strain)

Force and Moment Balance

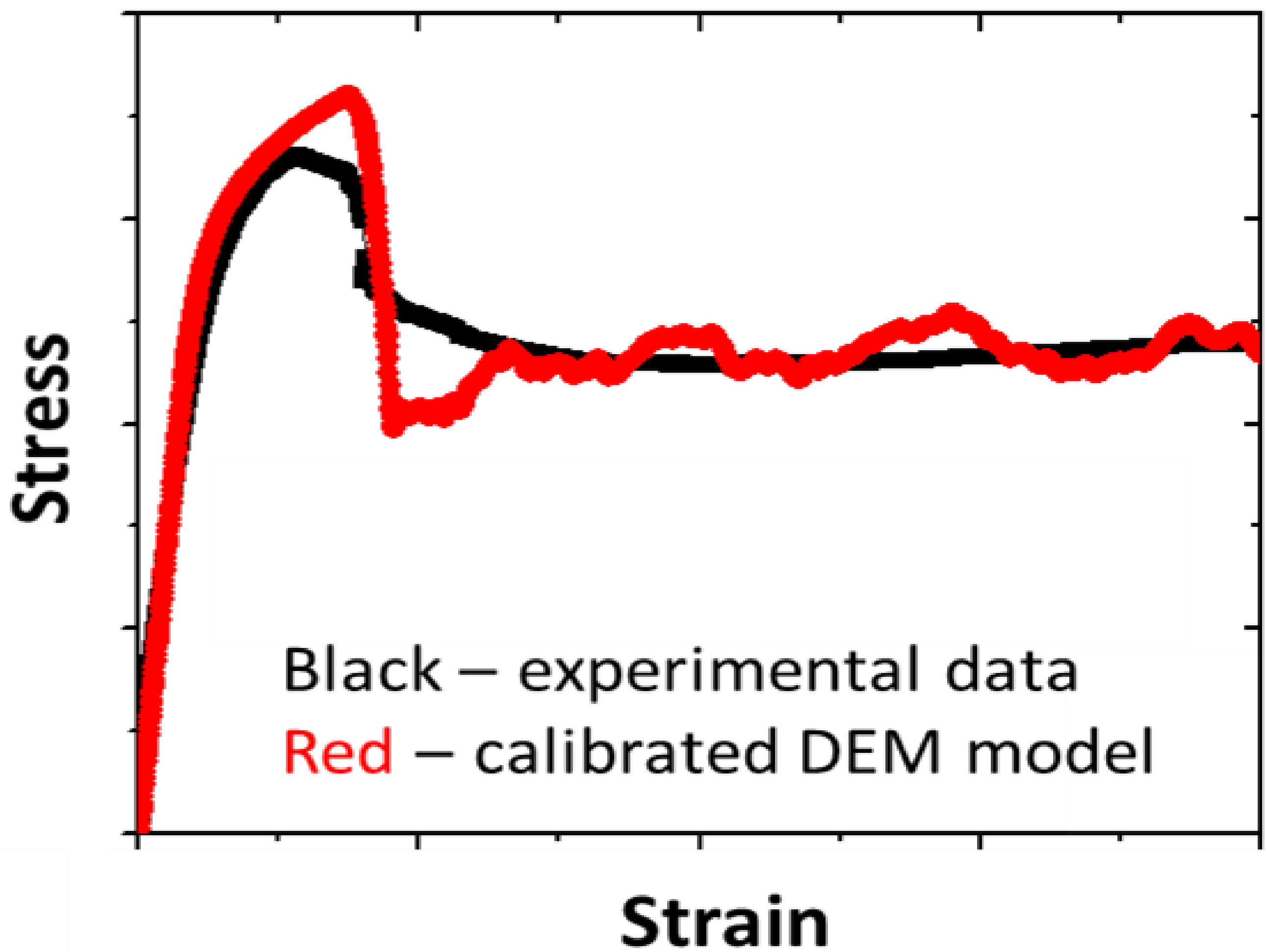
$$\vec{F}_{i,j} = k_n(d_{i,j} - d^0_{i,j}) + k_s \frac{1}{2}(\varphi_{i,j} + \varphi_{j,i})\vec{s}_{i,j}$$

$$\vec{M}_{i,j} = k_s d[\frac{\Phi}{12}(\varphi_{i,j} - \varphi_{j,i}) + \frac{1}{2}(\frac{2}{3}\varphi_{i,j} + \frac{1}{3}\varphi_{j,i})]$$

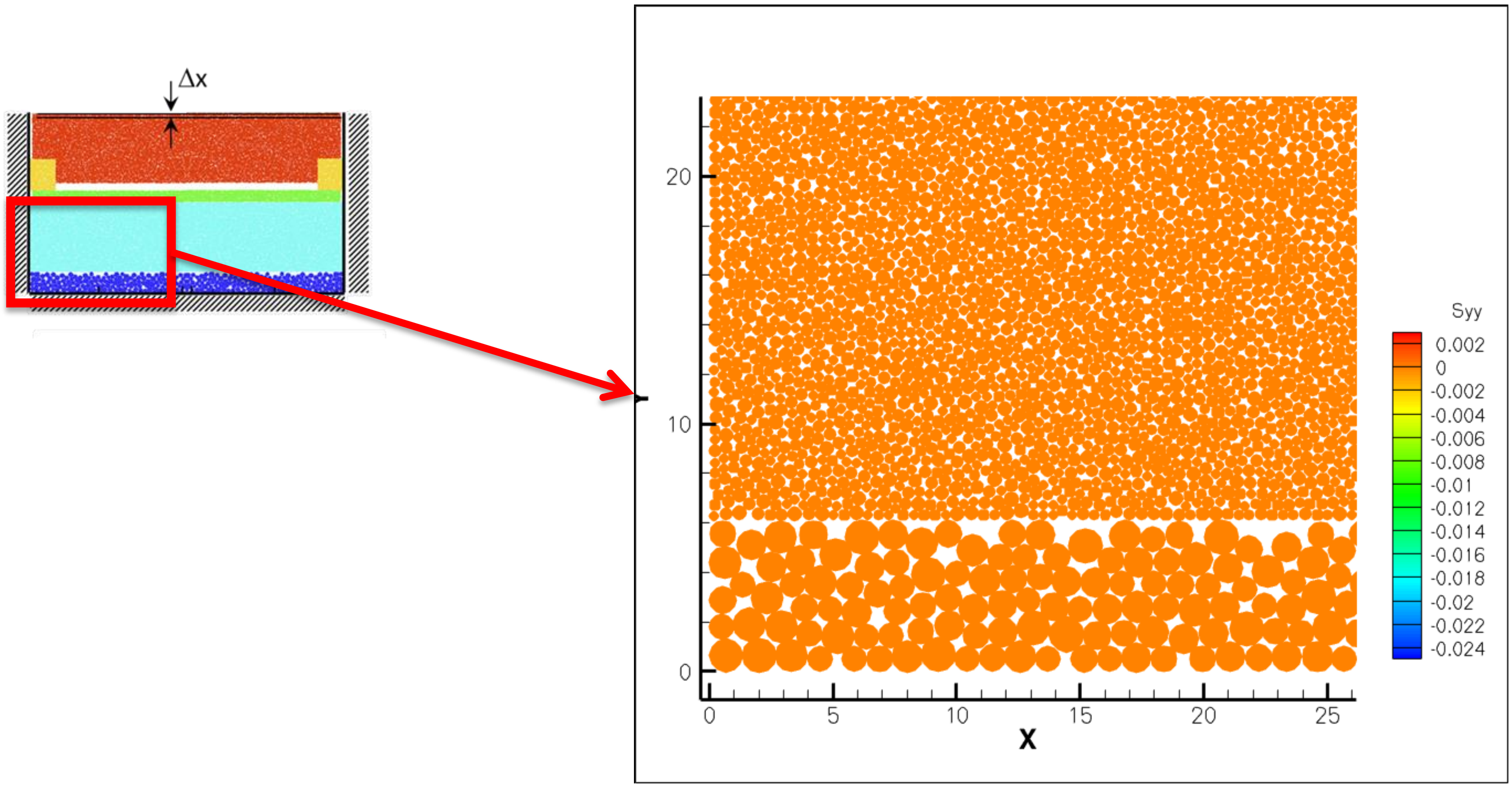
2D Model Setup



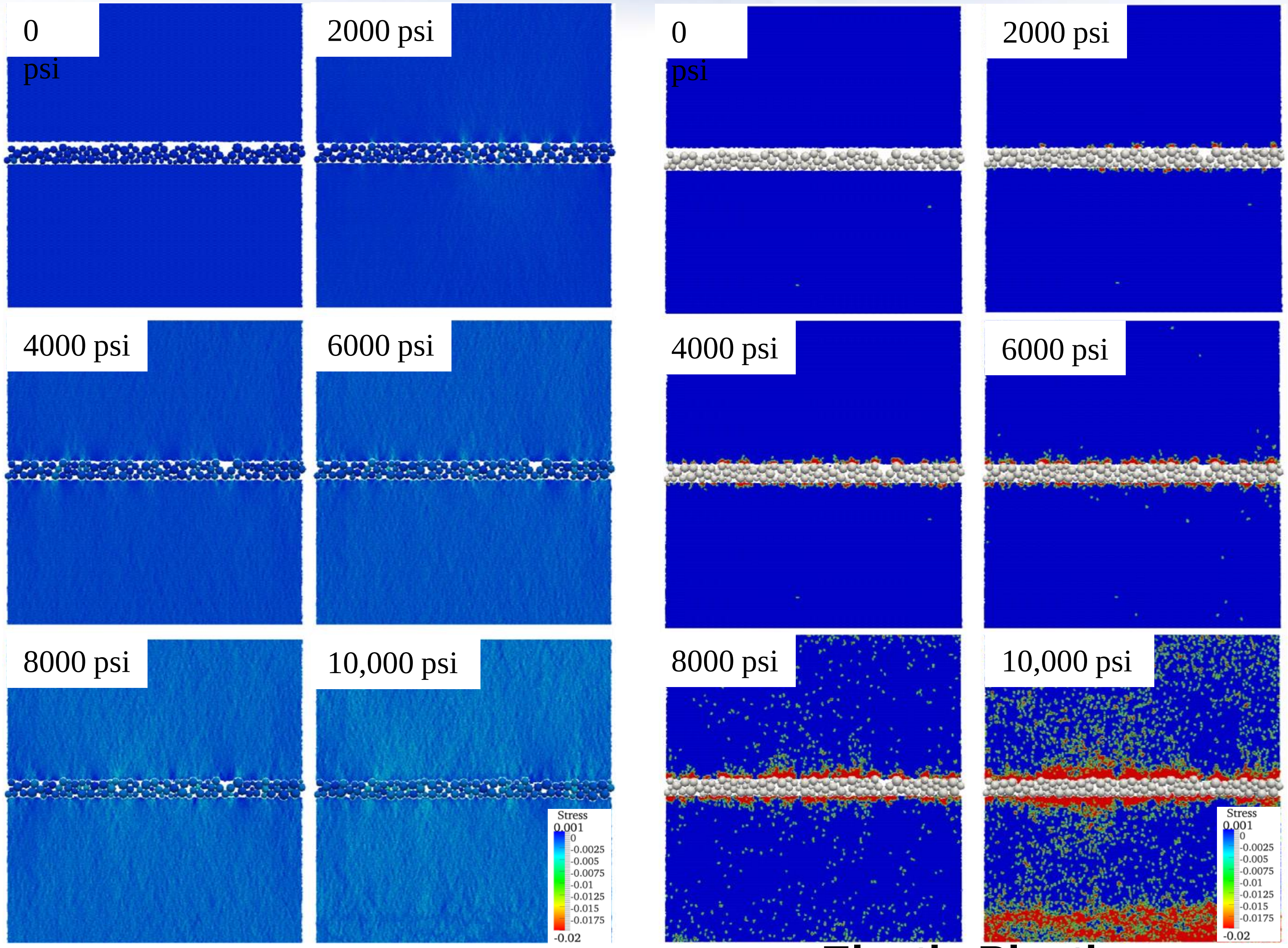
Model Calibration to Shale



Example of Proppant Re-Arrangement in Standard Groove Cooke Cell

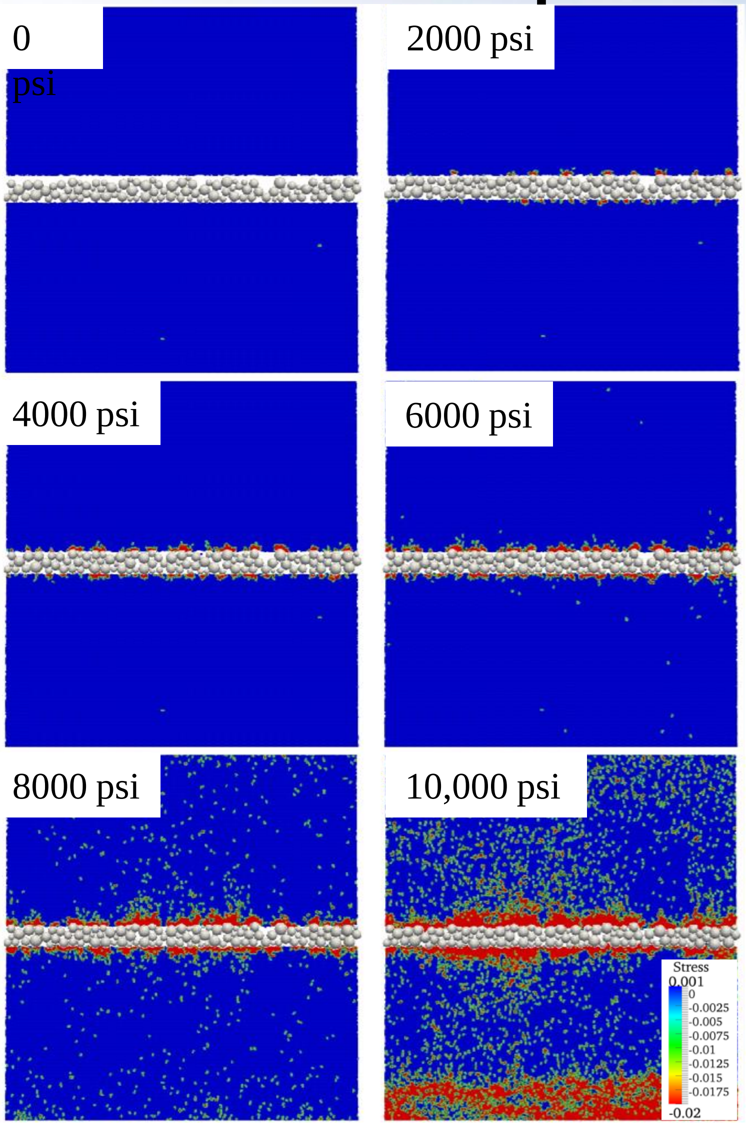


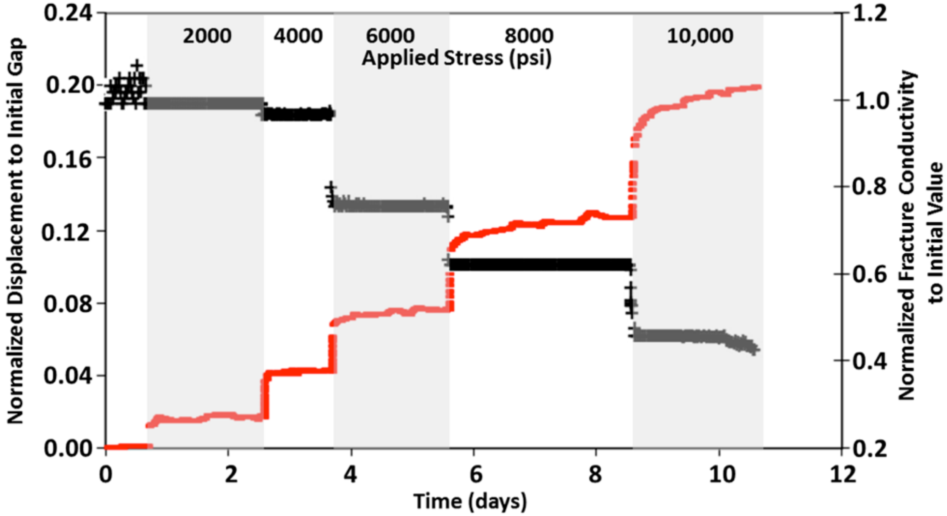
Model Results



Pure Elastic **Elastic Plastic**

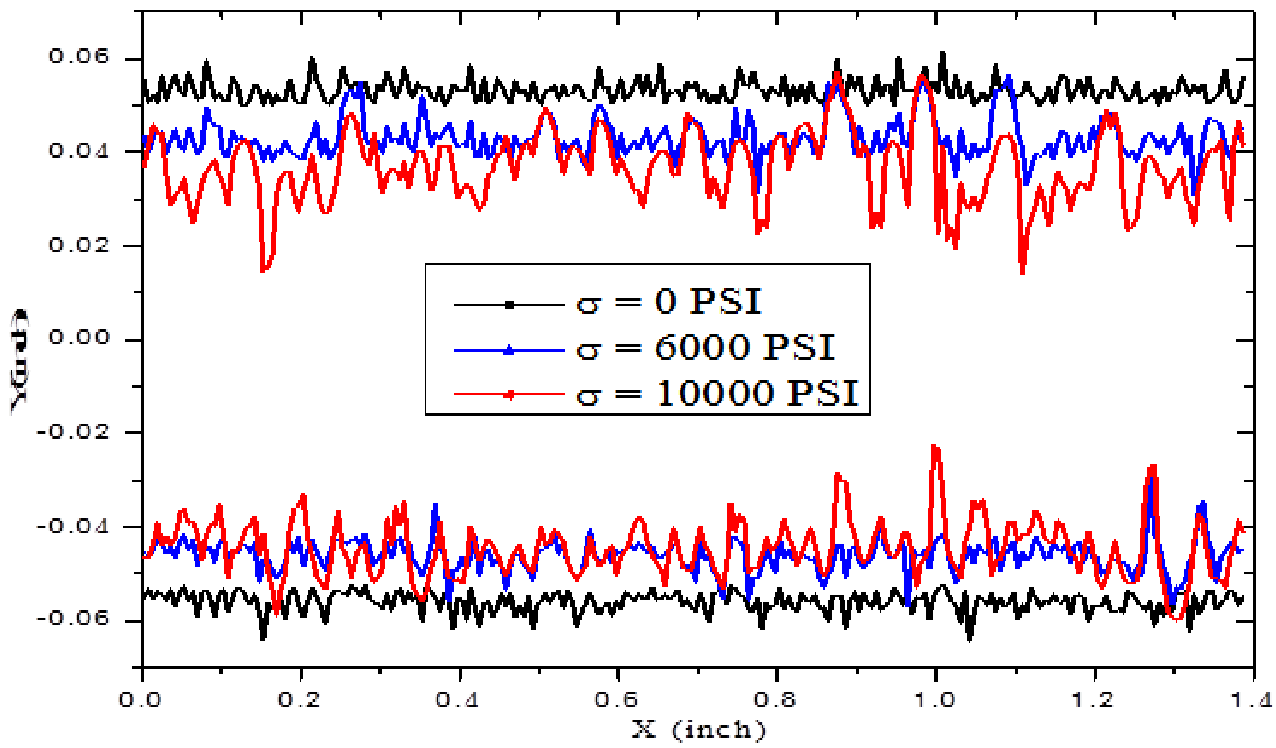
Development of plastic zone





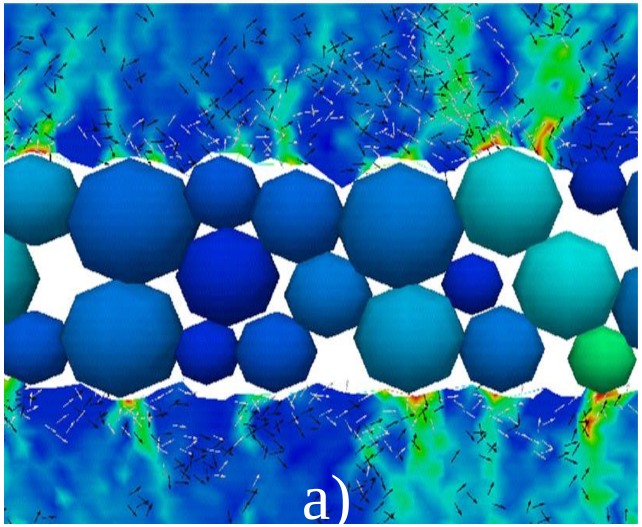
Elastic Plastic

Aperture reduction due to embedment

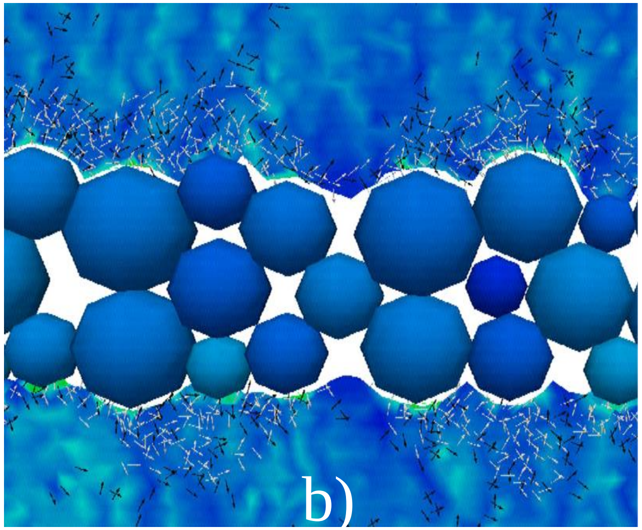


Damage to Fracture walls

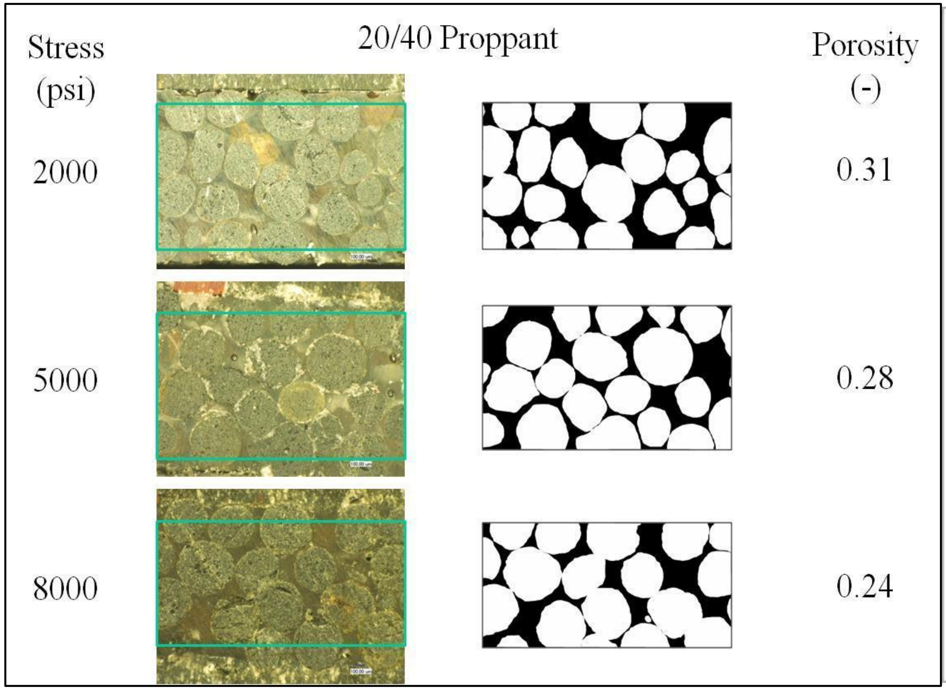
Pure elastic model

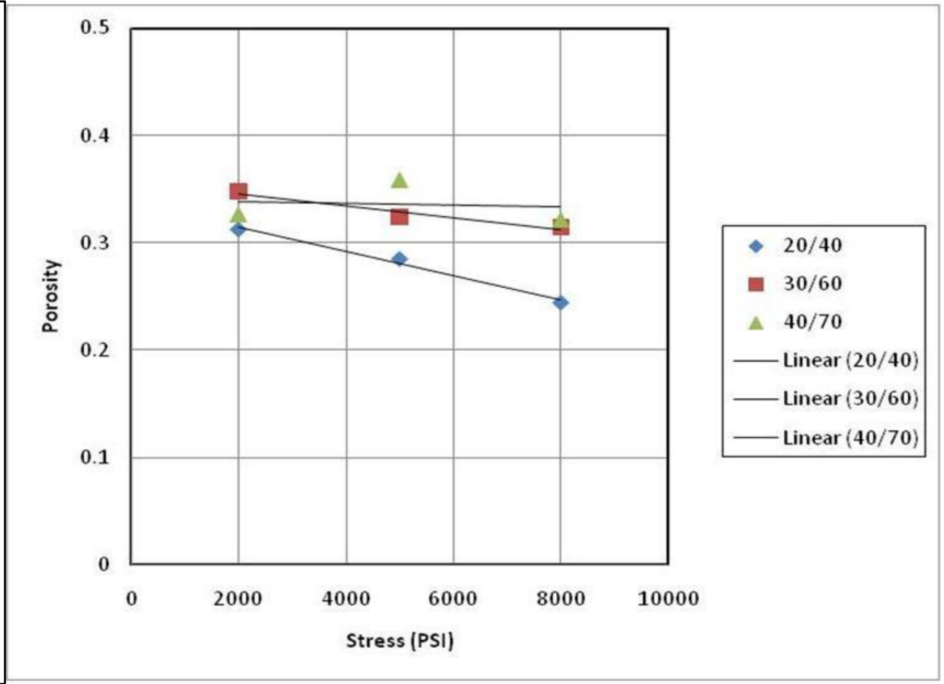


Elastic-plastic model



Proppant Rearrangement

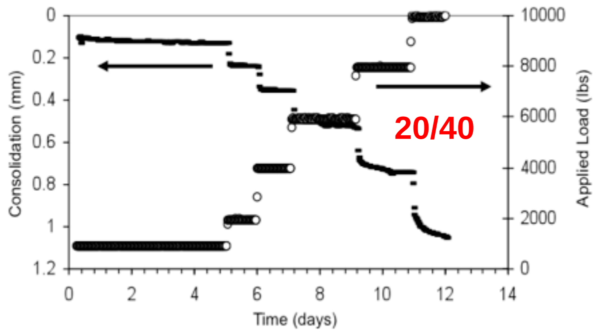


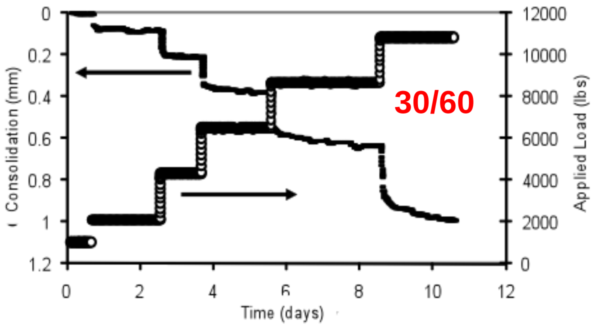


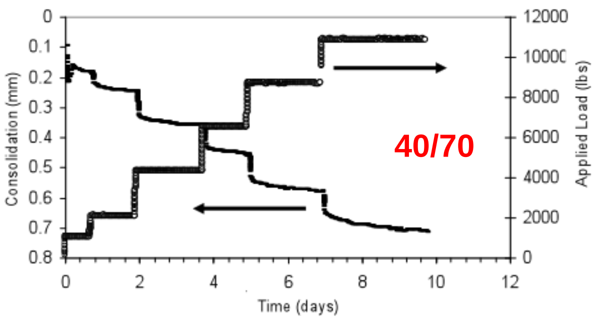
Cross section view at 100x magnification of the 20/40 proppant at a final stress level of 2000, 5000, and 8000 psi stress, the binary distribution of the proppant and the surrounding epoxy, and the calculated porosity from the binary image

Model-Experiment Comparison

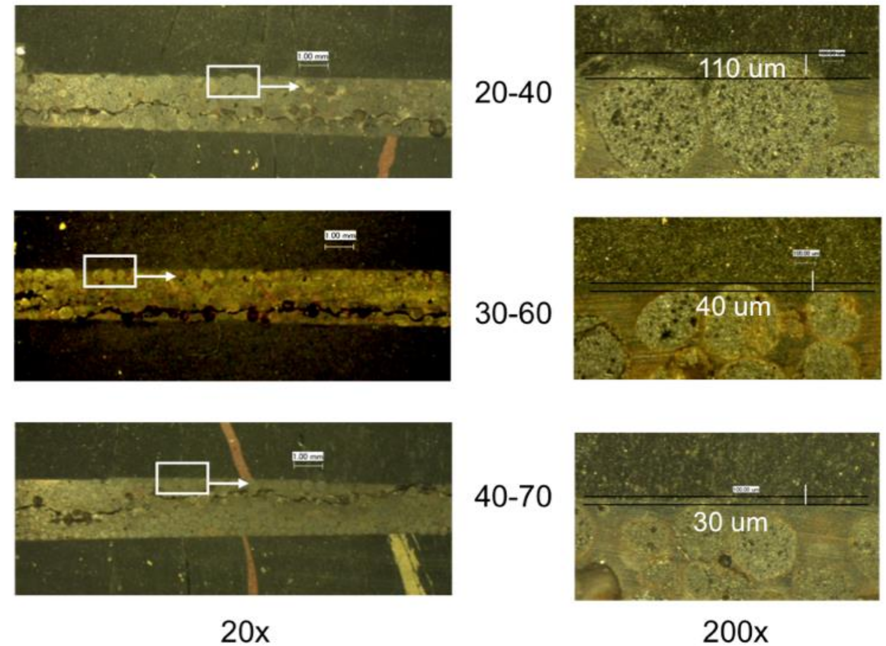
Measured consolidation of samples vs. stress







Cross sections of proppant-filled fractures stabled with a clear epoxy after experiments



Comparison between the simulated and measured proppant embedment

Proppant Size	Modeled Proppant embedment (mm)	Experimental Proppant embedment (mm)
20/40	0.10	0.11
30/60	0.06	0.04
40/70	0.02	0.03

➢***Experimental results are very consistent with modeling results!***

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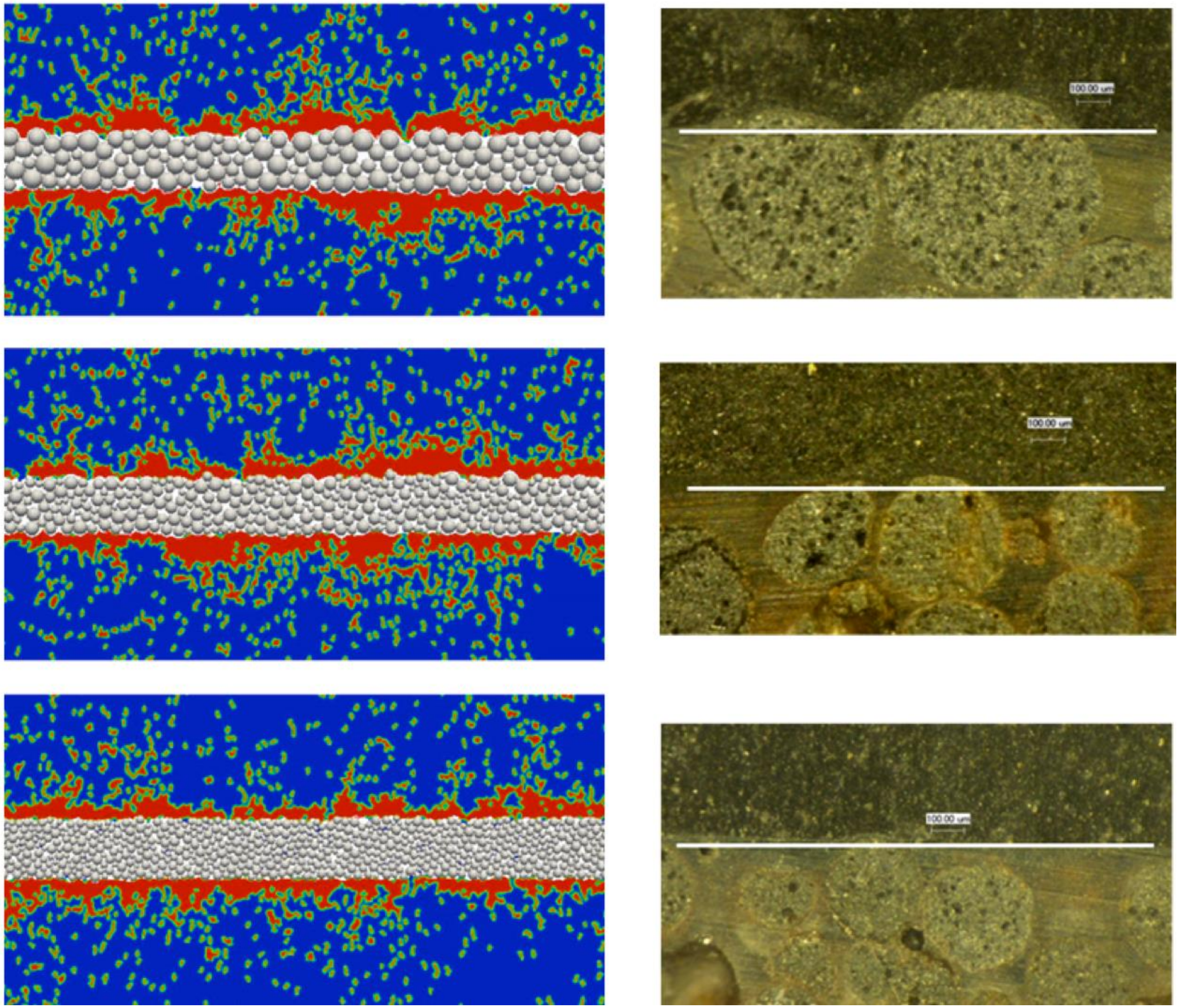
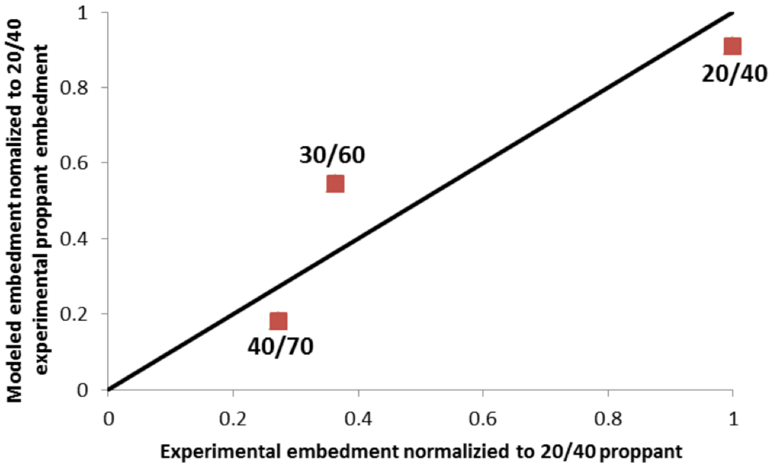
Extent of Plastic zone as f(proppant size)



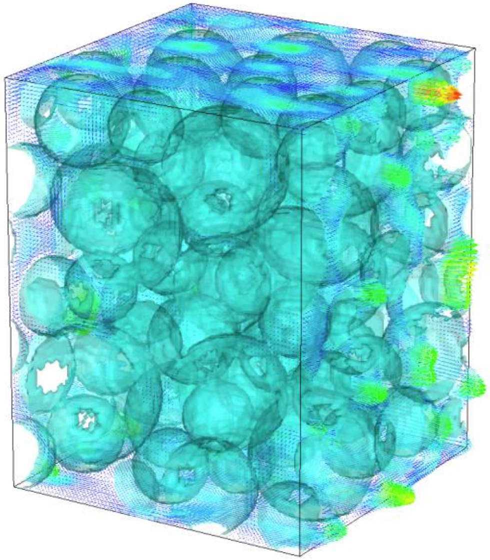
Summary

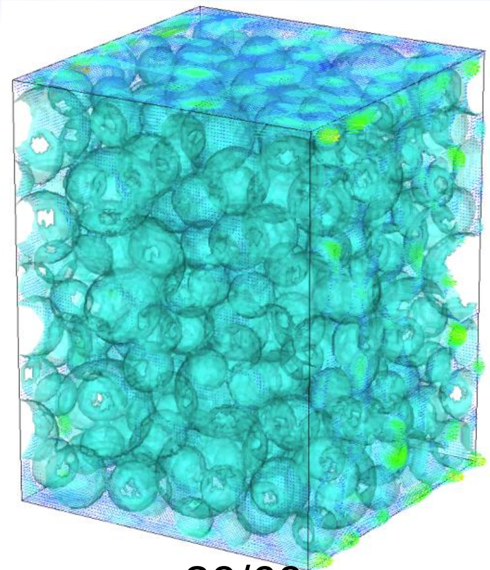
- Good agreement between elastic-plastic model and experimental results

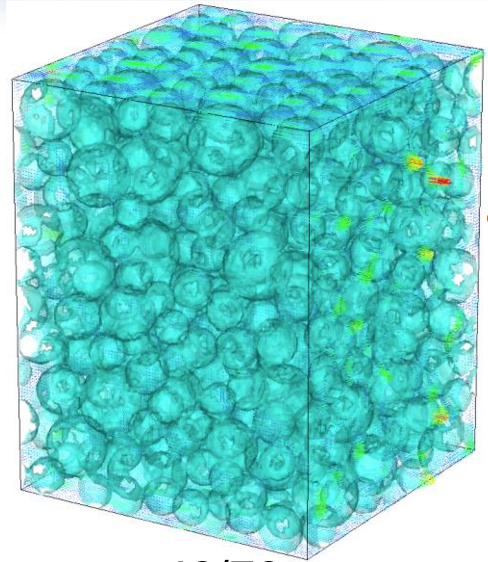


- Larger proppants will:
  - tend to embed sooner than smaller proppants
  - tend to embed more than smaller proppants
  - tend to create a plastic zone along the fracture wall sooner
  - tend to have a thicker plastic layer along the fracture wall

3D pore-scale flow model in propped fracture

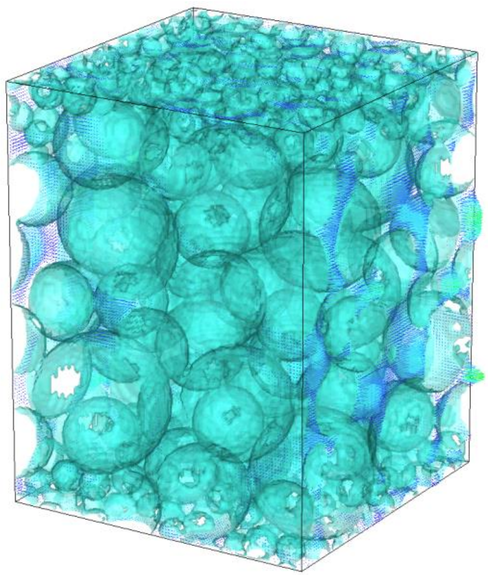


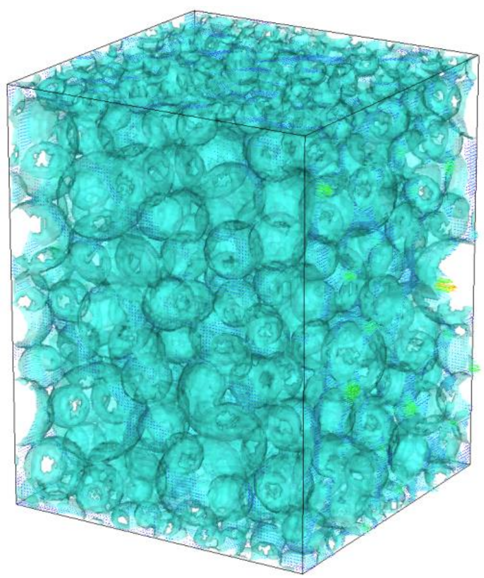


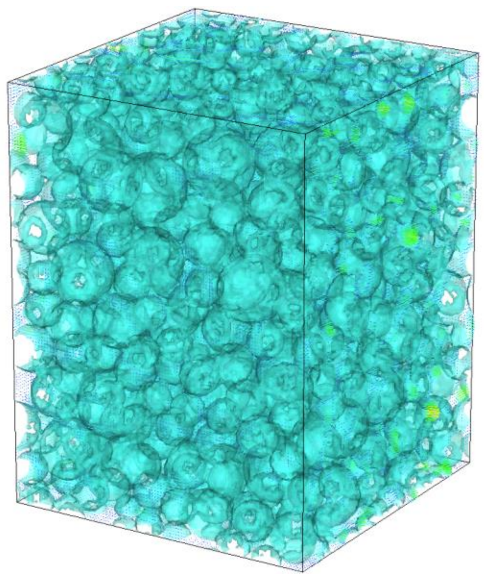


- Initial 0 psi load stress

- 20/40
- 30/60
- 40/70







- 14,000 psi load stress